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DEVELOPING A METHODOLOGY FOR THE EVALUATION OF MILITARY HYBRID ELECTRIC VEHICLE THERMAL MANAGEMENT SYSTEMS

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ABSTRACT

A method for the evaluation of military hybrid electric vehicle thermal management systems has been developed. The approach allows for the generation of a set of evaluation metrics for determination of the effectiveness of existing systems and the means to assess alternative concepts and advanced approaches. Further, through the use of a set of deterministic performance metrics the methodology allows for evaluation of performance margins for adverse boundary conditions and system operations.

The thermal management systems of military hybrid electric vehicles can face challenging performance goals under the burden of unfavorable operating conditions. The cooling requirements of engines, motors, and power electronics impose specific requirements on thermal management system performance in terms of threshold temperatures and heat rejection capability. In addition, vehicle packaging concerns impose restrictions in terms of both volumetric occupancy and system weight. Acknowledgement of these concerns has led to thermal management system evaluation metrics in two separate classes: performance-based metrics and packaging-based metrics.

Performance-based metrics allow for a means to determine whether a vehicle thermal management system can meet maximum thermal demands at the worst case boundary conditions. Further, this methodology establishes a design metric for quantifying thermal management system hotel loads. Performance metrics allow for a structured approach to identify system over-design and/or functional margin deficiencies under a worst-case operational scenario. This approach can be used for the evaluation of existing vehicle systems through operational data and conceptual designs through analytical performance predictions. The proposed methodology allows for the comparison of systems both within and across classes of vehicles. Further, this approach allows for the evaluation of system design maturity, identify potential areas of improvement and quantify significant technological advancements.

INTRODUCTION

The thermal management systems (TMS) of military hybrid electric vehicles face challenging performance goals. The system must successfully perform under unfavorable operating conditions and within vehicle-packaging-imposed restrictions. These restrictions limit the TMS volumetric occupancy and system weight but do not forgive any packaging associated thermal loads. Acknowledgement of these concerns has led to thermal management system evaluation metrics in two separate classes: performance-based metrics and packaging-based metrics. These metrics allow for the quantification of the effectiveness of existing systems and the means to assess alternative concepts and advanced approaches. Furthermore, the metrics can be used to evaluate performance margins for adverse boundary conditions and system operations.

Performance-based metrics allow for a means to determine whether a vehicle thermal management system can meet maximum thermal demands at the worst case boundary conditions. These metrics formulate a measure of the TMS hotel loads, thermal loads, and operational thermal margin. The latter can be used to identify system over-design and/or functional margin deficiencies under a worst-case operational scenario. Performance data necessary for the calculation of the operational thermal margin can be measured for existing vehicle systems or analytically predicted for conceptual designs.

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Packaging-based metrics measure the impact of the TMS as integrated in the vehicle structure. Due to the limited space on the vehicle, TMS components must be installed in constricted spaces. Oftentimes this results in unique mounting strategies specific to the component. Nevertheless, a military vehicle thermal management system can interact with most of the primary components in the hybrid electric power train. As such, the equipment needs to be catalogued into the appropriate category to insure equivalent treatment in the metric formulation. Component exclusive auxiliary equipment should be included in a component-level volumetric, weight or power density evaluation. Non-exclusive equipment such as pumps, heat exchangers and fans that serve multiple components need be included in system-level packaging considerations.

This paper outlines how a set of TMS evaluation metrics can be developed through the analysis of a conceptual, generic hybrid electric system. A structured methodology is outlined for the appraisal of existing systems at both the system- and component-levels. Lastly, the methodology is extended to address issues of system topology variations.

CATEGORIZING THE THERMAL MANAGEMENT SYSTEM

Evaluation of a vehicle Thermal Management System (TMS) must begin with intimate knowledge of the vehicle in question—architecturally and operationally. The architecture of the vehicle includes a listing of the various components and their layout on the vehicle structure. This knowledge allows each equipment to be cataloged as to account for their volume and weight. Furthermore, understanding the operation of the system allows for a determination of where to assign or how to estimate the component thermal loads.

The first task in the metric formulation is to differentiate between system and component related equipment. This is important in that component-level cooling equipment needs to be noted in order to have an accurate estimate of component power density. For example, the engine component will include the oil coolers/pumps, charge air coolers, water/fuel pump, and fuel cooler.

Auxiliary equipment need to also be identified and assigned to the proper component assembly. These components are those operating within a closed loop that has specialized cooling equipment. For example, all support equipment for cooling of an inverter would be assigned to that inverter component. This could be a pump required to raise the closed-loop coolant pressure as well as the heat exchanger required to subsequently transfer the heat from the closed-loop to the primary system loop. Furthermore, the volumetric bookkeeping for the individual components must also include ancillary non-system components like required electrical wiring and connectors, plumbing fittings, etc. In this way, the component cannot be taken to be just the shrink-wrapped component volume.

Vehicle packaging considerations may make assignment of equipment between system or component level difficult. For example, due to packaging restrictions, a specific component must be mounted in a location that is farther away from the heat exchanger such that it requires substantial plumbing considerations—i.e. brackets, valves, fittings, lines, etc. In this case, assignment of the subsequently necessary equipment should be to the system-level. However, in the end, as long as the items are consistently catalogued in future evaluations, their contribution will be fairly accounted for in the metrics.

Specialized payloads and architectural outliers would also need to be identified. However, they should be exclusive of the base system and so be handled separately. These may be one-time use items or required only for specific missions—for example, an extra battery pack for use only in a specific scenario.

Once the equipment has been catalogued, determination of the system metrics can proceed. A baseline vehicle TMS will be used to describe the formation and functionality of the proposed metrics. For this paper, the chosen climatic condition will be a "hot dry day with a 49°C ambient temperature". Note that if so desired other climatic and/or operational conditions could be similarly evaluated as to generate a table of metric values for the individual component as well as entire system. The derived values for this baseline system (component) can then be used to quantitatively judge a system (component) candidate via comparison of their metric values.

BASELINE MODEL AND ASSUMPTIONS

The baseline vehicle chosen for this paper is one that is a full hybrid electric in the 30-ton class. The engine equipment (oil pump, oil cooler, water pump, fuel cooler, etc.) will be catalogued with the engine block. The charge air cooler (CAC) will be assumed to be of the air-to-air variety and listed as "component-level" equipment affiliated with the engine block. Furthermore, the thermal management system will be assumed to not require sub-ambient operation. Only thermal loadings due to mobility

operations are considered here. Loadings due to mission electronics, ambient solar, or human occupancy will be assumed negligible. Also, packaging optimization will not be considered in the present discussion.

From an operational standpoint, the baseline vehicle will see a 31 ton loading condition with 7 square meters of frontal area, a drag coefficient (C_D) of 0.8, and a 35 lb/ton rolling resistance. The tractive effort (TE) ratio for the baseline vehicle is given in Figure 1. Thus, for a 40 mph continuous climb up a 5% grade, the tractive effort ratio is 0.074 while for a 55 mph continuous flat, the TE is 0.026. Note that the tractive power ratio is assumed to be 15 kW/ton such that for a vehicle weight of 30 tons, the tractive power required is 450 kW or 225 kW per side.

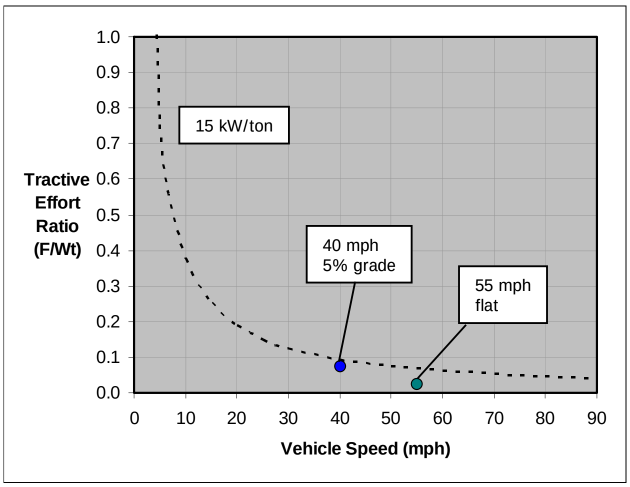


Figure 1: Tractive Effort versus Vehicle Speed

The architecture of the baseline vehicle is that of a generic hybrid system with a DC bus distribution, 500-hp prime power generator, and energy storage system connected through a DC/DC converter. As mentioned earlier, the required tractive power or mechanical demand will be 225 kW per side. Furthermore, there will be a 3.73 kW (5 hp) auxiliary cooling pump and a cooling fan for ultimate heat removal from the heat exchanger stack. Also, all component efficiency will be assumed to be 95%.

For the climatic and operational design conditions given above, the required fan power was calculated to be 34 kW. Derivation of this value will be given later in this paper. Taking the fan power into consideration results in a requirement of 210.6 kW from the battery. Figure 2 shows a schematic of the energy balance across the DC bus as derived for this scenario. Note that all electronic component and motor thermal loads were calculated using the prescribed efficiency assumed above.

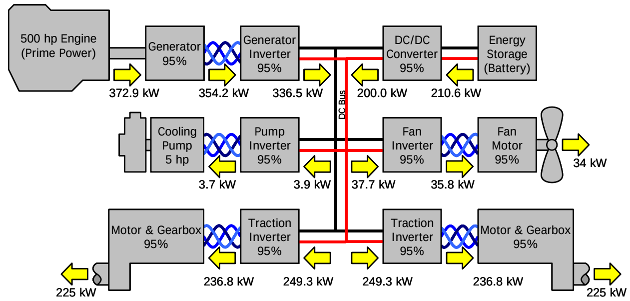


Figure 2: Energy Balance for Baseline Case

The previous energy balance along with the component prescribed efficiencies gives the thermal loads for the individual components. Further assumptions include that the cooling pump/inverter and batteries are air-cooled while the electronics and motors are water-cooled with either an ethylene glycol-water (EGW) or propylene glycol-water (PGW) mixture. The thermal loadings in the baseline system for the present design point are depicted in Figure 3. Note that the engine block and oil cooler results in 86.2 kW and 53.6 kW of waste heat, respectively. The CAC is assumed to be packaged with the engine and assumed to be an air-to-air heat exchanger.

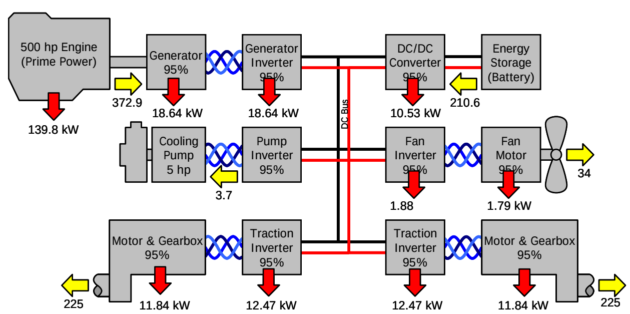


Figure 3: Thermal Audit of Baseline System

The thermal management system of the baseline vehicle is assumed to be divided into two cooling circuits. The low temperature (LT) circuit addresses the vehicle electronics and motors and is responsible for 102.9 kW in total heat load. A high temperature (HT) circuit is then responsible for the engine needs (139.8 kW). Note that all of the components on the LT loop are plumbed in parallel with a 70°C maximum allowable coolant temperature and a 40 gallon-per-minute (gpm) flow rate. As for the HT coolant, it is driven by the engine cooling pump (and therefore assumed to be an engine component-level thermal equipment). The HT limits are assumed at 80 gpm with a 110°C maximum allowable coolant temperature. The heat exchangers are assumed to be

in series with respect to cooling air. This setup is schematically shown in Figure 4.

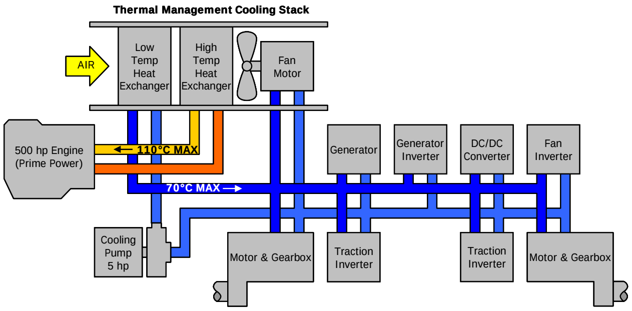


Figure 4: TMS Schematic

Derivation of the 34 kW fan power noted earlier is done using knowledge of the thermal loading conditions, HX core performance, and vehicle packaging restrictions. For the baseline vehicle, the design calls for the two heat exchangers to be in series (see **Figure 5**) with respect to the air flow (i.e. the heat exchangers share a common air flow) with the LT unit being the first in line. Because of this, plumbing considerations impose a four-pass heat exchanger layout. Note that a width restriction is imposed due to other baseline vehicle packaging constraints.

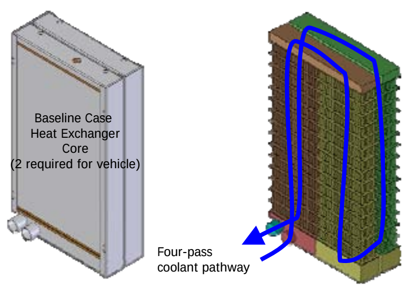
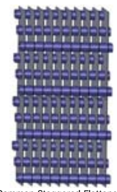
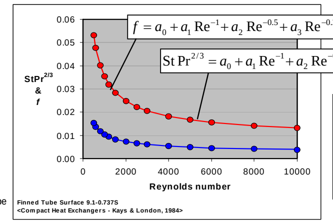


Figure 5: Heat Exchanger Core Nomenclature

The first task in estimating the fan power is to determine the heat transfer for a specific core geometry using a Stanton number correlation such as that shown in **Figure 6**. Use of this in addition to the vehicle packaging restriction will establish the heat exchanger core size (i.e. frontal area and depth) and flow requirements. Since the fan ultimately adds to the vehicle thermal loading, this process is an iterative one. Once a fan power is determined, its estimated losses are inserted back into the estimate for the total vehicle thermal loading and the process repeated until convergence is met.

For the baseline model, the chosen heat exchanger aspect ratio dictates that 10,000 cubic feet per minute (CFM) of air is required to meet the heat rejection needs assuming that the 49°C air is dry. Note that the air flow is assumed to be uniform and well-mixed between the LT and HT heat exchanger core sections. Furthermore, the cores are assumed clean and tube wall conduction resistance is negligible.





Constants	f	$\mathrm{StPr}^{2/3}$
a_0	0.0096	0.0048
a_1	8.2596	1.0171
a_2	0.8230	0.3837
a_3	-0.0338	-0.0301

Friction Factor & Stanton Number Correlation Coefficients

Surface Designation	Tube Arrangement	Fin Type	Tube Length (parallel to flow)		Tube Width (normal to flow)		Fins/in	Hydraulic Diameter		Fin Thickness		Free Flow/Frontal Area	Heat Transfer Area/Total Volume		Fin Area/ Total Area
			in	10^{-3}m	in	10^{-3}m		ft	10^{-3}m	ft	10^{-3}m		ft²/ft³	m²/m³	
9.1-0.737S	Staggered	Plain	0.737	18.7	0.100	2.5	9.1	0.01380	4.21	0.004	0.102	0.788	224	735	0.813

Baseline Heat Exchanger Geometrical Properties <*Compact Heat Exchangers* – Kays & London, 1984>

Figure 6: Exemplar of Tabulations and Correlations

Once the flow requirement is determined, the next step is to estimate the expected air pathway pressure head loss. This can be achieved using friction factor correlations for the HX core. Estimates can also be included for the ducting pathway using textbook correlations while contributions from the inlet/exhaust ballistic grill can be estimated using manufacturer data.

Use of friction factor correlations for the heat exchanger core along with duct/grill loss data enables formation of an estimate of the pressure drop as a function of air flow. Once that is determined, fan performance curves can be used to determine the required fan power. For this round of design, the heat exchangers have been assumed to be stacked and a stack performance curve is assumed to be applicable. The stack performance curve (pressure as a function of flow rate) is shown in Figure 7 and is mapped against the fan curves.

The baseline case calls for 10,000 CFM and approximately 18 in H_2O of pressure head. Note that this is a rough initial estimate. A more precise estimate can be found using a more detailed CFM analysis of the actual pathway inclusive of the ballistic grills, heat exchanger cores, and flow routing ductwork. After several iterations of this fan power analysis, the operation design point was established at 10,000 CFM, 6000 RPM fan speed, and 34 kW of fan power consumption.

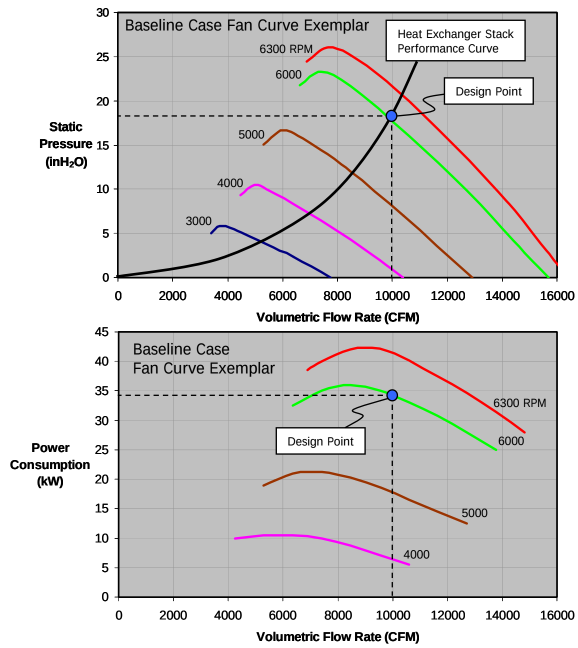


Figure 7: Fan Curves as a Function of Volumetric Flow Rate (CFM)

METRIC FORMULATION

A quantitative evaluation of the TMS of the baseline vehicle can now be made using its derived performance. The first two metrics proposed evaluates the TMS packaging. Note that a metric value can be generated for each of the component-level sub-system as well as for the entire TMS. In this example, only the system level metrics will be calculated. The packaging envelope needs to be evaluated as to how it impacts the vehicle. This includes overall vehicle size impact rather than just the volume of the component (i.e. “round component in a vehicle’s square hole” effect) as shown in Figure 8. The “outside the circle” contribution can become extremely significant when considering plumbing runs, fittings, valves, etc. Examples of components to be included in the system weight and volume estimates include (but are not limited to) heat exchangers, pumps, fans, controllers, reservoirs, plumbing, ductwork, grills, and coolant inventory. For the baseline system considered in this paper, the TMS volume is estimated to be 0.85 m^3 (30 ft^3) and weighs 1100 lbs.

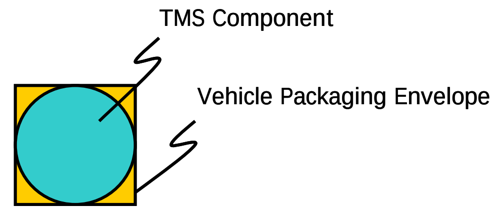


Figure 8: Vehicle Packaging Overflow

The *TMS Weight Metric* can now be determined by comparing the TMS weight to the overall vehicle weight audit such that for the baseline vehicle:

$$\begin{aligned} \text{TMS Weight Metric} &= \frac{\text{TMS Weight}}{\text{Vehicle Weight}} \\ &= \frac{(1100/2000)}{30\text{ ton}} \times 100 = 1.8\% \end{aligned} \tag{1}$$

A similar value can also be generated for the *TMS Volume Metric* in which the weights are replaced by their respective volumes. These two metric gives the evaluator an idea as to the size of the packaged system. Furthermore, since the TMS weight (volume) is normalized to the vehicle weight (volume), the metric is applicable across a range of vehicles.

The *Hotel Load Metric* gives a measure of the cost of the energy required to remove the system thermal load. This metric compares the hotel loads of the vehicle to the deliverable vehicle tractive power. Once again, scaling with respect to vehicle power affords the applicability to a host of vehicles instead of a specific one. Note that this metric value is for a specific operational condition and, as such, can have multiple values if other situations are evaluated. For the baseline case described above, the hotel loads are composed of 3.7 kW of pumping power and 34 kW of fan power. Meanwhile, the vehicle is capable of 450 kW of tractive power. Thus,

$$\begin{aligned} \text{Hotel Load Metric} &= \frac{\text{Thermal Hotel Load}}{\text{Tractive Power}} \\ &= \frac{(3.7 + 34)}{450} \times 100 = 8.4\% \end{aligned} \tag{2}$$

The *Thermal Load Metric* gives a measure of the thermal efficiency of the system. It compares the vehicle thermal load to the deliverable tractive power. For example, the baseline case has thermal loads for the LT loop of 102.9 kW and HT loop of 139.8 kW. Recall that the total deliverable tractive power is 450 kW. Thus, the *Thermal Load Metric* is:

$$\begin{aligned}\text{Thermal Load Metric} &= \frac{\text{Vehicle Thermal Load}}{\text{Tractive Power}} \\ &= \frac{(102.9 + 139.8)}{450} \text{ x } 100 = 53.9\%\end{aligned} \tag{3}$$

A measure of the capability of the TMS can be derived from the *Operational Thermal Margin Metric*. This metric compares the maximum heat rejection capability to the design point. Note that the design point heat rejection was determined to be 242.7 kW. The maximum system capability is estimated using the maximum throughput of the fan and the associated heat rejection at that CFM at the operational ambient conditions for the design point. For the baseline system, this was calculated to be 253 kW. Thus,

$$\begin{aligned}\text{Operational Thermal Margin} &= \frac{\text{Maximum - Design Point Load}}{\text{TMS Maximum Capability}} \\ &= \frac{(253 + 242.7)}{253} \text{ x } 100 = 4.1\%\end{aligned} \tag{4}$$

A large value for this metric would indicate that the TMS can afford some "fine-tuning". This would allow for trade-offs in TMS performance for cost/weight/volume improvements.

As mentioned earlier, the metric values found above for the baseline vehicle are for a specific climatic condition and operational point. Other design points will yield different values for the *Hotel Load*, *Thermal Load*, and *Operational Thermal Margin* metrics. These can easily be tabulated to form a baseline package. Any proposed TMS change will then go through similar evaluations and generate its own set of metric values. The latter can then compared to the former to evaluate the merits of the modifications/replacement. Likewise, different operational setpoints can be evaluated. For example, the impact of higher operating temperatures on system performance/capability can be investigated.

The generality of the proposed metrics along with their normalization to the investigated vehicle system allows great flexibility in their use. They are easily applicable to both conceptual and existing vehicles. The primary difference is that for the former, the operational thermal margin is estimated while for the latter actual performance data can be used to determine actual performance limitations. In either case, the generated metrics afford a quantitative descriptor of the effectiveness of the vehicle TMS that facilitate evaluation of proposed modifications to the system performance.

It must be noted, however, that the metrics cannot be used as the sole reason to modify/replace an existing vehicle TMS. Other evaluation factors would need to be considered prior to making a judgment on the competing/proposed system design change. For example, the total cost of the replacement would need to be considered. Total cost should cover the cost of the component as well as necessary installation expenditures. Another criterion to consider is the robustness of the sub-system. Will it ease the installation of the component/TMS? How rugged is the unit? Still another criterion is the readiness of the system. How mature are the components and system as a whole? How readily available are the parts that make up the system? How easy is it to operate? Do you need special personnel to run it? These must all be factored in the decision-making. The metrics proposed here merely provide a way to quantitatively compare/evaluate the proposed changes.

CONCLUSION

Five TMS metrics have been proposed and exemplified via a baseline vehicle example. These metrics are labeled as *TMS Weight*, *TMS Volume*, *TMS Hotel Load*, *TMS Thermal Load*, and *Operational Thermal Margin*. The metrics allow for a quantitative measure of a vehicle TMS in terms of performance and operation. Evaluation of different design points for a vehicle TMS allows for a tabulation of the baseline TMS performance. Future proposed system or component changes would then be evaluated at the same design points to generate its own set of metric tabulation. The two tables can then be compared to determine the merit/deficit of the TMS alteration.

The metrics are easily applicable to both conceptual and existing vehicles due primarily to their generality. As such, evaluating component alternatives in either platform is straightforward. However, the final decision whether or not to field the TMS design change cannot be based on the metrics alone. Total cost, robustness (simplicity) of installation, and readiness of components need to be factored in the decision.